ADMINISTRATIVE INFORMATION

1. **Project Name:** Fiber Optic Sensor for Industrial Process Measurement and Control (CPS# 1604)

2. **Lead Organization:** MetroLaser, Inc.
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Irvine, CA 92614

3. **Principal Investigator:** Dr. Peter DeBarber: phone (949) 553-0688, fax (949) 553-0495
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4. **Project Partners:**

Bergmans Mechatronics LLC	Mr. John Bergmans
University of California, Irvine	Dr. Vince McDonell
GE EERC	Mr. Pete Maly

5. **Date Project Initiated:** 09/04/99

6. **Expected Completion Date:** 03/31/05

PROJECT RATIONALE AND STRATEGY

7. **Project Objective:**

We set out to develop a new commercial temperature and chemical sensor primarily for high temperature gas combustion measurement and process control applications. The goals of our project were to maintain accuracy, large dynamic range, affordability, ruggedness, and high temporal resolution. We have met these goals by combining low-cost telecom components with our proprietary software and spectroscopic measurement strategy. MetroLaser successfully tested and demonstrated several prototype sensors in the hot gases and flames of industrial combustors where the results proved to be in excellent agreement with complimentary observations using chemiluminescence and thermocouples.

8. **Technical Barrier(s) Being Addressed:**

Current temperature and chemical sensors rely on intrusive proves, often with extractive sampling. Such strategies are fragile and require frequent calibration and maintenance. In addition, measurements may be too slow for real-time process control or monitoring applications. An optical sensor based on near infrared tunable diode laser absorption offers an approach to circumvent these challenges. We are pursuing this strategy for industrial combustion applications and therefore face a new set of challenges. Present technical barriers being addressed include:

- increase the path length spanned by the probing laser beam for large operations
- assess the acceptable degree of particulate loadings
- increase the sensitivities for the CO and CO_2 measurements
- optimize calibration for more turbulent, heterogeneous flows

9. Project Pathway:

As we move from the laboratory scale demonstrations in Phase II to large-scale field site tests in the follow-on contract, we identified several improvements and modifications. To effect the transition, we undertook a program to:

- identify suitable large-scale field test sites that (1) meet the demonstration needs of the DOE EERE IPT goals and (2) offer a credible test that we may use as a marketing tool
- model conditions with respect to temperature, pressure, chemical concentrations, and path length for the identified field test facilities
- design hardware interface for specific tests
- perform laboratory level calibration runs
- modify data acquisition software for specific tests
- assess commercialization potential
- identify commercialization partners

10. Critical Technical Metrics:
Baseline Metrics:

- Temperature Measurement Range: 900 - 2500 K
- H_2O Concentration: 60 ppb/m
- Accuracy: 50 K
- Sample Rate: 200 Hz
- Path length: 30 cm to 10 m

Possibility to add CO_2 and CO:

- CO_2 concentration: 3 ppm/m
- CO concentration: 30 ppm/m

Project Metrics:

- Extended Temperature Measurement Range: ambient – 3000 K
- Sample Rate: 10 kHz
- Path length in excess of 10 m

PROJECT PLANS AND PROGRESS

11. Past Accomplishments:

This project is the continuation of a project that was initially begun under the ITP Sensors and Automation IOF, and received SBIR Phase I and Phase II funding. Under the SBIR program, we have successfully:

- Simulated spectra and relevant absorption features
- Verified the accuracy of the HITRAN database
- Demonstrated a two-laser temperature and H2O sensor on an industrial combustion chemical vapor deposition torch
- Demonstrated a single-laser temperature sensor on industrial burner
- Simultaneously accessed two spatial locations
- Identified and probed transitions insensitive to ambient H_2O
- Demonstrated adequate sensitivity to combustion temperatures

- Demonstrated high spatial and temporal resolutions
- Demonstrated excellent correlation with chemiluminescence, well-suited for active control applications
- Designed and built a portable prototype system for follow-on demonstration tests

12. Future Plans:

Our future plans fall within the scope of our follow-on funding. The major milestones to be accomplished are to:

- Measurement at two spatial locations simultaneously (inlet and outlet of gas stream)
- Measurement over a pressure range of ~1/3 to 10 atm (1 atm = 14.7 PSI)
- Measurement of temperature over a range spanning 400 – 900 K (0˚C =273.15 K)
- Measurement of water vapor concentration over a range spanning 6 – 80%
- Measurement time less than 1 second

13. Project Changes:

Under the current program there have been no changes in the project direction or timetable.

14. Commercialization Potential, Plans, and Activities:

The commercialization potential is difficult to quantify, however, based on discussions with our partners, we conclude that niche markets exist. For example, the Phase II sensor was deployed at MicroCoating Technologies, Atlanta, GA on a Nanomiser^{TM} spray combustor nozzle used for precision chemical vapor deposition (CVD). Novel semiconductor electronics, exotic fiber preforms, high performance optical components, and complex MEMS systems are just some of the products that require accurate and precise control of the deposition process. Control of the temperature within the spray plume is a critical parameter that affects the vaporization rate of the coating precursors. Until now, no rapid, non-intrusive measurement method for active control of temperature in a turbulent spray combustor was available. Conventional fine-wire thermocouple devices, although relatively inexpensive, cannot withstand the high temperature environment and frequently drift out of calibration. Our system demonstrated that such measurement can be accomplished routinely in a production setting, in the presence of vibration, flame luminosity, temperature and pressure extremes and particle interferences. Savings directly attributable to system use include reduced material and energy consumption as well as lower maintenance costs. The added benefit of precise control of the deposition process translates to major savings from less waste due to out of spec product. MicroCoating Technologies estimates that use of the diode laser sensor instrument in pilot production may result in 40% reduction in out of spec products, and 25% energy savings due to improved deposition conditions.

Another example that we are presently researching is for coal-fired power plant applications. Projected energy savings are unknown, but potentially non-zero. For example by maintaining furnace exit gas temperatures below the ash softening temperatures, the occurrence of slag build-up and associated heat-transfer losses, could be reduced. The use of soot blowers, which use steam or compressed air, would also be reduced.

By allowing precise measurement and control of furnace temperature on startup, boiler tube failures due to thermal stresses can be minimized, thereby reducing unscheduled plant shutdowns for boiler tube repairs.

By maintaining furnace exit gas temperatures below the ash softening temperatures, the occurrence of slag build-up and associated maintenance costs are reduced. Potential damage caused by large slag formations falling from the top of furnace can be avoided.

A multi-beam system could measure the temperature of individual burners in a pulverized-coal furnace. This technique could allow hot, NOx-producing burners to be identified and repaired.

A third example that we are pursuing through demonstration testing in our follow-on contract is to focus on the need for simultaneous non-intrusive temperature and water vapor measurements in the hydrogen reforming industry for fuel cell applications. Present approaches to sensing these parameters are inadequate. Temperature measurement of the gaseous streams at the inlets and outlets of various catalytic reactors used in fuel cell fuel processor systems such as SMR and auto-thermal reforming (ATR) reactors are needed for operation, control and alarm/shutdown systems. A temperature control system may be used to ensure that the system is operating at its optimum temperature and to detect if the catalyst is overheating due to improper gas flow control or mixing of reactants. Overheating conditions may lead to catalyst damage resulting in downtime and expensive repairs. Fine wire based temperature sensors (such as thermocouples), although relatively inexpensive, suffer from short and long term instrument drift, failure under high temperatures and low corrosion resistance, all of which can also lead to costly system downtime. The diode laser sensor system is inherently immune to drift and can withstand high temperatures and corrosive conditions. The diode laser sensor can be readily integrated into a feedback control system with fail-safe capability. For example, if the primary control of the air, steam and fuel flows to the reactor is by mass flow meters, the air meter may drift or fail to indicate air flow; this condition might result in undesirably large air flows being directed to the reactor. Under such a scenario, the catalyst would rapidly increase in temperature due to combustion of the incoming stream. Before the catalyst could become damaged, the diode laser sensor would detect the start of the exotherm and make appropriate adjustments.

For water measurement in both a SMR process and an ATR process, the water content in the process gases is critical to prevent carbon formation, which leads to catalyst fouling and can result in permanent catalyst damage. Currently liquid water is metered at the inlet to the system, but often it is sent into multiple heat exchangers in various sections of the process before being mixed with the process gases. Depending on the size of the heat exchangers and the rate of steam formation, varying levels of steam (water vapor) may be present in the process gases. Measurement of water vapor concentrations would be most helpful for fuel cell and fuel processor systems of all types, but this measurement is challenging with traditional sensors. Measuring the water vapor in the inlet or outlet of the reforming process or at various other places within a fuel cell or fuel processor system would provide a much more direct and reliable method of control. Our sensor could provide an accurate measurement of water concentration at almost any point in these systems without compromises due to interferences, harsh environment (e.g., corrosive or reducing conditions), limited physical access or sampling system complexities. Additionally, water content in the reformate stream into the fuel cell is critical to fuel cell operation and lifetime. Being able to directly measure the water content would be a highly preferred method of control/monitoring versus deriving an estimate of water concentration from various inlet liquid water meters and assumptions of upstream fuel processor performance and operating conditions.

Present commercialization activities include the recent signing of a limited exclusive North American distributorship agreement with Bergmans Mechatronics LLC. We are currently negotiating similar agreements for coverage in Europe and Japan.

15. Publications and Presentations

1. T.P. Jenkins, V.S. McDonell, and P.A. DeBarber, "Calibration Considerations of a Non-intrusive Temperature Sensor for Gas Turbine Combustion," submitted for consideration to the 43rd AIAA Aerospace Sciences Meeting and Exhibit, Jan. 10 – 13, 2005, Reno, NV.

2. T.P. Jenkins, V.S. McDonell, and P.A. DeBarber, "Fiber-coupled Diode Laser Sensor for Temperature and H2O in Harsh Environments," submitted for consideration to the AFRC-JFRC 2004 Joint International Combustion Symposium Meeting, October 10-13, 2004, Maui, HI.

3. T.P. Jenkins, V.S. McDonell, and P.A. DeBarber, "Multi-channel, Fiber-coupled Diode Laser Sensor for Harsh Environments," submitted for consideration to Chemical and Physical Sensors for Extreme Environments at the 2004 IEEE Sensors Meeting, Oct. 24 – 27, 2004, Vienna, Austria.

4. T. P. Jenkins, P. A. DeBarber, J. Shen, and V. G. McDonell, "Diode Laser Sensor for Temperature and H2O Measurements in High Pressure Environments," AIAA Paper No. 04-0456, American Institute of Aeronautics and Astronautics, 42nd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 5 - 8, 2004.

5. T. P. Jenkins, P. A. DeBarber, J. Shen, and V. G. McDonell, "Time-resolved In-situ Temperature Measurements in a Model Industrial Burner using a Tunable Diode Laser," 2003 Western States Section/Combustion Institute, Los Angeles, CA, October 20-21, 2003.

6. T.P. Jenkins, P.A. DeBarber, J. Shen, and V.G. McDonell, "A Simple, Rugged Diode Laser Sensor for Temperature Applied to Measurements in a Low NOx Burner," 2003 AFRC International Symposium, Livermore, CA, October 16-17, 2003.

7. T. P. Jenkins, P. A. DeBarber, and J.D. Trolinger, "A Single Laser Diode Sensor for H2O and Temperature Measurement in Combustion Applications," 12th Gordon Research Conference on Laser Diagnostics for Combustion, Queen's College, Oxford, UK August 17-22, 2003.

8. T. Jenkins, P. DeBarber, and M. Oljaca, "Diode Laser Sensor for H2O and Temperature Applied to Measurements in an Industrial Combustion Vapor Deposition Torch," 3rd Joint Meeting of the U.S. Sections of the Combustion Institute, Chicago, IL, March 16 – 19, 2003.

9. T. Jenkins, P. DeBarber, and M. Oljaca, "A Rugged Low Cost Diode Laser Sensor for H2O and Temperature Applied to Measurements in a Spray Flame," AIAA Paper No. 03-0585, American Institute of Aeronautics and Astronautics, 41st Aerospace Sciences Meeting and Exhibit, Reno, NV, January 6 - 9, 2003.

10. T.P. Jenkins, E. Scott, P.A. DeBarber, V. McDonell, and T. DeMayo, "A Rugged, Low-cost Diode Laser Sensor for H2O and Temperature," ISA Paper No. 4005, the Instrumentation, Systems, and Automation Society 48th International Instrumentation Symposium, San Diego, CA, May 5 – 9, 2002.